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COMMUNICATION BLACKOUT AT RE-ENTRY

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SUMMARY

Procedures are outlined for computing the approximate attenuation of radio signals transmitted through the shock layer of a large re-entry vehicle and the communication-blackout time.

A review of the computation methods and of the availability of the data needed in these computations indicates that approximate methods with simplifications applied in most of the phases of the computation represent, at present, one of the most fruitful approaches for obtaining estimates for the communications "blackout" at re-entry. Based on this concept, approximate equations are derived for the re-entry attenuation. The derived equations are then applied to the re-entry of a manned space capsule (MA-6 Mercury flight) into the earth's atmosphere.

INTRODUCTION

When a space vehicle re-enters the earth's atmosphere at high velocity after an orbital or a space mission, layers of ionized air form around the vehicle and interfere with the transmission of radio signals to and from the vehicle. Aerodynamic heating causes the air in the flow field around the vehicle to become ionized and the resulting plasma interacts with the radio waves. If the velocity is sufficiently high, a complete interruption of the communication operations is the consequence. This so-called "blackout" of radio transmission was anticipated and was observed regularly during the re-entry phases of manned orbital flights in the Mercury program.

Since similar effects were experienced earlier on flights of intercontinental missile nose cones, analyses of these effects were carried out and a limited amount of literature exists on the subject. Some examples of related articles are those by Taylor[1], Lin[2], and Ellis[3]. More recent reports and publications related to manned space flights are those by McCabe[4], Marrone[5], and Tischer[6].

Reviewing analyses of re-entry communications shows that the problem of computing the attenuation of signals caused by the plasma sheath is very complex due to the large number of parameters involved in the computations. Taking into account all important thermodynamic, physical, chemical, and flow field phenomena and those related to the wave propagation makes exact computations almost impossible. Inaccuracies of data necessary in the computations also reduce the value of accurate computations. Under these conditions, estimates of the re-entry communications blackout based on approximate computation seems to be the best practical solution to this problem at present. With the approaching activities in suborbital and interplanetary flights, the re-entry problem will gain important and accurate methods of the blackout prediction and eventually its prevention will become necessary.

In this report approximate computation methods for estimates of the attenuation of radio signals during re-entry will be considered which are applicable to large space vehicles typical for manned space flight.

The flight conditions will be discussed first, followed by a consideration of the flow field and the electrical properties of the plasma sheath surrounding the vehicle. The

third part will deal with the wave propagation aspects. Combination of the results yields an approximate relation for the attenuation through the plasma sheath which also can be used for the determination of the blackout duration, its beginning and termination.

FLIGHT DYNAMICS AT RE-ENTRY

A vehicle re-entering the earth's atmosphere from an orbital flight has a velocity somewhat below 8 KM/sec (25.5 KFT/sec) at an altitude of about 120 KM. With decreasing altitude the vehicle encounters the effects of the atmosphere. A shock wave forms ahead of the blunt heat shield typical for the Mercury vehicle heating the air in this region to about 6000 degrees Kelvin. The vehicle becomes surrounded by a flow field of hot air and decelerating forces begin to reduce its velocity. A few minutes later, depending on the re-entry angle, the deceleration reaches a maximum at an altitude of about 50 KM. It is during this period of high deceleration and high heating that communication is interrupted by the plasma sheath. Figure 1 shows the dynamics of the re-entry in a velocity-altitude diagram. This type of diagram is very convenient and will later be used repeatedly. The diagram indicates the approximate altitude as a function of the velocity typical for re-entry flights of the Mercury program.

VEHICLE-INDUCED ENVIRONMENT

After the brief consideration of the flight dynamics at re-entry, it seems appropriate to deal more in detail with the environment induced by the re-entering vehicle. The mechanisms of the effects which determine the electrical properties of the medium in the vicinity of the vehicle are of particular interest.

The re-entering vehicle moving at hypersonic velocities produces a complex flow pattern in the surrounding medium. A shock wave with a sharp shock front forms ahead of the vehicle as indicated in Fig. 2. Behind the front, pressure, density, and temperature increase many times over the normal ambient values. The figure also shows the various regions of the flow field with the names clearly indicating the structure. The greatest increase in temperature and density occurs behind the shock front in point A in the vicinity of the stagnation point S_x (velocity = 0). In this region between the shock front and the

front portion of the vehicle, the air flow is subsonic. Farther back, the air expands, the flow becomes supersonic, and the gas parameters, density, and temperature decrease. At the rear section and in the rear of the vehicle, the flow becomes turbulent.

The high kinetic energy of the particles of the air entering the flow field region of the vehicle causes numerous physical and chemical reactions in this region. The conversion of the flow energy into internal energy results in dissociation and ionization of the constituents of the air. The function of atomic oxygen and nitrogen as dissociation products has particular interest since they contribute to large numbers of charged particles, ions and electrons, by ionization which forms the plasma sheath. The ionized particles, mainly the electrons, interact with the electromagnetic waves traveling through the plasma sheath. Attenuation, phase effects, refraction, and reflection of the waves during the travel through the plasma sheath are the consequences.

A simplified qualitative indication of the major processes encountered in the environment of the vehicle at re-entry is shown in Fig. 3 in an altitude-velocity diagram. The dotted lines show the onset of the various reactions indicated in the diagram depending on the flight parameters, velocity and altitude. Since these processes are statistical in nature actually no sharp lines can be drawn; however, they may be used to indicate the macroscopic behavior.

The preceding considerations are indicative that the environment induced by the motion of the vehicle has a very complex structure. This is particularly the case since the reactions are continuously in a dynamic flux and equilibrium actually is never fully reached. In reality, the number of reactions is very much larger than that considered here and shown in the diagram, so that an exact analysis of these phenomena represents a formidable task.

ELECTRICAL MEDIUM PROPERTIES IN A SIMPLIFIED FLOW-FIELD MODEL

The electrical properties of the plasma surrounding the vehicle can be expressed by the electron density and collision frequency. These quantities are related to the gas parameters, temperature and density, and depend on the constituents. Knowing these properties of the plasma as a part of the flow field permits the solution of the wave propagation problem as a separate step of the computation. As a simplification, equilibrium data of the flow field are applied to this consideration since the sizes of the re-entry vehicle and the flow field dimensions seem to be large in comparison with the relaxation distance. If this assumption

later might turn out not to be justified, a correction can be introduced by a factor in the later presented equation.

A review of the literature indicates that the values of temperature and density of air as a function of altitude and velocity are at present known only behind a normal shock and at equilibrium. Evaluation of these quantities yields the electron density and the collision frequency. Approximate values of these data are shown in Fig. 4 in an altitude-velocity diagram.

In considering the electrical properties at any point in the flow field (see Fig. 2) the corresponding data, electron density and collision frequency, can be taken into account by factors in relation to the values of these quantities in the stagnation region behind the normal shock. The review of typical flow fields in the literature has shown[6] that the distribution of the electron density across the shock layer in perpendicular direction to the walls at the after-section of the re-entering body can be approximated by a Gaussian function. It is found that the collision frequency, on the other hand, remains approximately constant across the shock layer. Under these conditions, the maximum value of the electron density, the constant for its exponential decrease, and the value of the collision frequency near the body are the representative figures for the electrical properties within the flow field across the shock layer. The effect of the boundary layer in the vicinity of the body can be neglected taking into account the comparatively small thickness of this layer in comparison with the shock layer. With these figures, the plasma properties along the path of the electromagnetic waves crossing the plasma sheath can be described. The electron density N_e and the collision frequency ν as a functions of the distance y from the wall of the vehicle are hence

$$N_e = N_s F_1 \exp(-ky^2) \tag{1}$$

and

$$\nu = \nu_s G_1, \tag{2}$$

where N_s and ν_s are the quantities behind the normal shock at the stagnation region and where F_1 and G_1 are geometry factors which indicate their decrease along a near-body stream line. The constant k can be related to an equivalent shock-layer thickness δ_{eq} which, under the assumption of a constant electron density in the shock layer gives the

same attenuation as the layer with exponentially decreasing density. The magnitude of the electron density in the equivalent shock layer is equal to the actual density near the body. We can write

$$N_s = N_s F_1 \exp [-0.79 (y/\delta_{eq})^2], \tag{3}$$

where δ_{eq} in turn can be related to a length L across the shock layer where the electron density has decreased by a factor 10^{-2}. Both quantities are interrelated by $\delta_{eq} = 0.467$ L.

WAVE PROPAGATION ACROSS THE PLASMA SHEATH

In accordance with the rest of this consideration, simplifying assumptions are made for solving the wave propagation problem. Plane waves are herewith assumed. With the exception where the antenna size is small compared with the wave length, this assumption may be justified. An additional simplification is made by assuming that the collision frequency is small compared with the operational frequency. Along the re-entry glide path of a manned space flight, in contrast to ballistic missiles, this condition is usually fulfilled. With these assumptions, the attenuation in DB can be expressed as an approximation by

$$R^{DB} = 8.868 \int_o^{\Delta} a \, d \, y, \tag{4}$$

where a is the attenuation constant in Nepers per unit length and where Δ is the depth of the shock layer. The attenuation is given as an approximation by

$$a \approx p^2 q/2. \tag{5}$$

The quantities p and q represent the values of the plasma and collision frequencies normalized with respect to the operational frequency ω. These quantities are given by

$$p^2 = (\omega_p / \omega)^2 = N_e e^2 / m_e \epsilon_o \omega^2 \tag{6}$$

and

$$q = \nu / \omega, \tag{7}$$

where e is the charge of an electron and m_e is its mass. For further details with regard to the derivation of the above equations, reference is made to the literature[4, 6]. Rather extensive bibliographies can be found in Ref. 6 and in a publication by Dirsa[8]. Since a varying electron density across the shock layer was assumed, reflections at the boundary of the layer near the shock front can be included in a matching loss related to the matching conditions of the antenna and taken into account by reduction of the antenna gain.

SIMPLIFIED EQUATION FOR THE ATTENUATION BY THE PLASMA SHEATH

A closed-form representation of the attenuation can now be written down based on all these simplifying assumptions. The attenuation by the plasma sheath, in DB has the form

$$R_{tot}^{DB} \approx 0.012\, N_s\, \nu_s\, F_1\, G_1\, \delta_{eq} / f^2, \qquad (8)$$

where f is the operation frequency in cycles per second. The other quantities were previously defined.

It should be mentioned that the geometry factors F_1 and G_1 actually are functions of altitude and velocity. Evaluation of published flow-field data indicates, however, that these quantities can be assumed constant for rough estimates of the blackout conditions. The geometry factors can be obtained from theoretical flow field considerations, or they can be determined by the evaluation of attenuation measurements carried out in real flight with real size vehicles at re-entry. Evaluation of measurements carried out during one flight yields the geometry factors which can be used in later flights.

Concerning the validity of Eq. (8), it should be noted that it can be applied during the re-entry in direction toward lower altitudes down to a point shortly before the actual blackout of communications starts. Under these conditions, the plasma along the transmission path is underdense. After that, the attenuation increases very rapidly to extremely large values. In this region and during blackout when the plasma is overdense different equations have to be applied. After blackout, when the plasma layer becomes underdense again, the equation can be applied again with caution depending on the normalized collision frequency in the vicinity of the antenna.

APPLICATION OF THE DERIVED COMPUTATATION METHOD

The method described in the preceding sections was applied to the computation of the attenuation of signals at various frequencies at the re-entry of the manned space capsule MA-6 of the Mercury program. As a first step, the plasma and collision frequencies behind a normal shock in the stagnation region were determined as a function of altitude and velocity. The diagram in Fig. 4 was used for the determination of these frequencies for the trajectory data shown in Fig. 1. The geometry factors F_1 and G_1 were computed then as rough estimates from published flow field data (cylinder with spherical nose). The equivalent shock layer thickness was found from the geometry of the capsule and of the estimated flow field. With these values, the attenuation was tentatively computed for

one frequency. The geometry factor F_1 was then corrected according to the measured values of the attenuation at this frequency. The attenuation computed at a different frequency was then compared with that observed in the actual flight. Figure 5 shows the observed signal-strength decrease indicating the attenuation in DB and the computed values for a frequency of 260 MC. The result indicates that the developed method is suitable for estimates of the blackout time and attenuation at the re-entry of large space vehicles from orbital flights.

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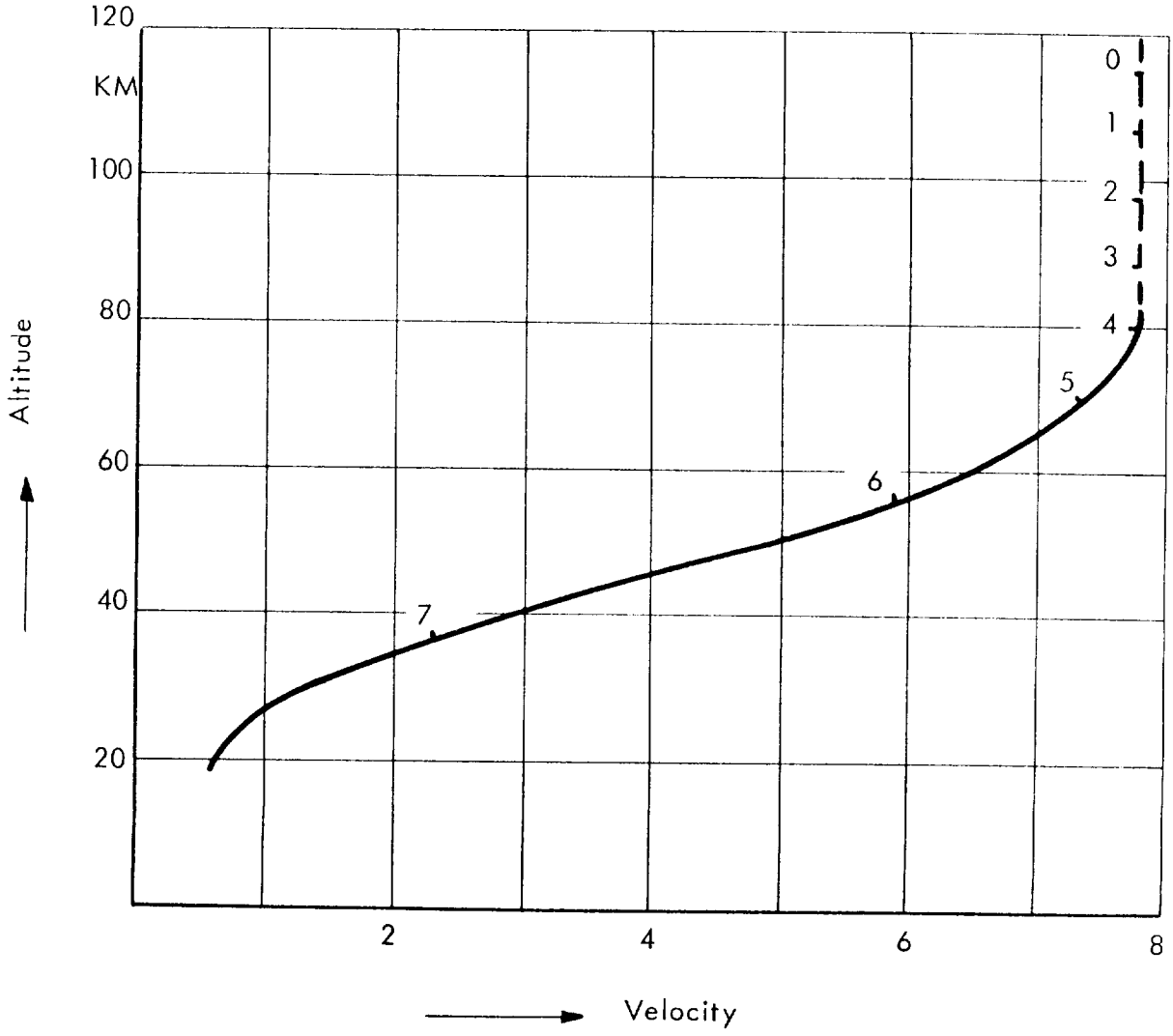

Figure 1 Approximate re-entry trajectory for a manned orbital flight. (Relative time markers in minutes).

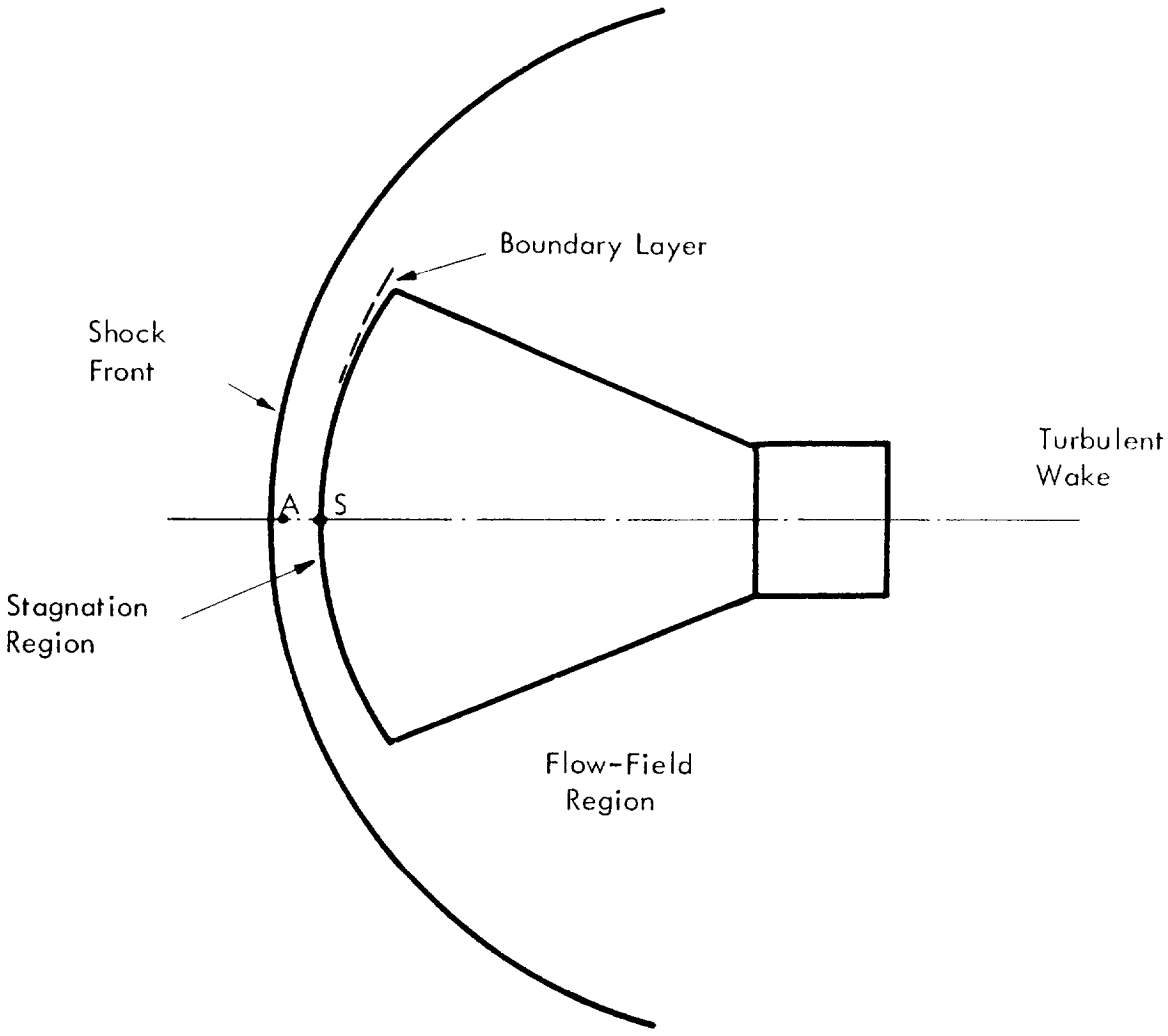

Figure 2 Flow-field structure around a space capsule at re-entry.
A: Region behind a normal shock.
S: Stagnation point.

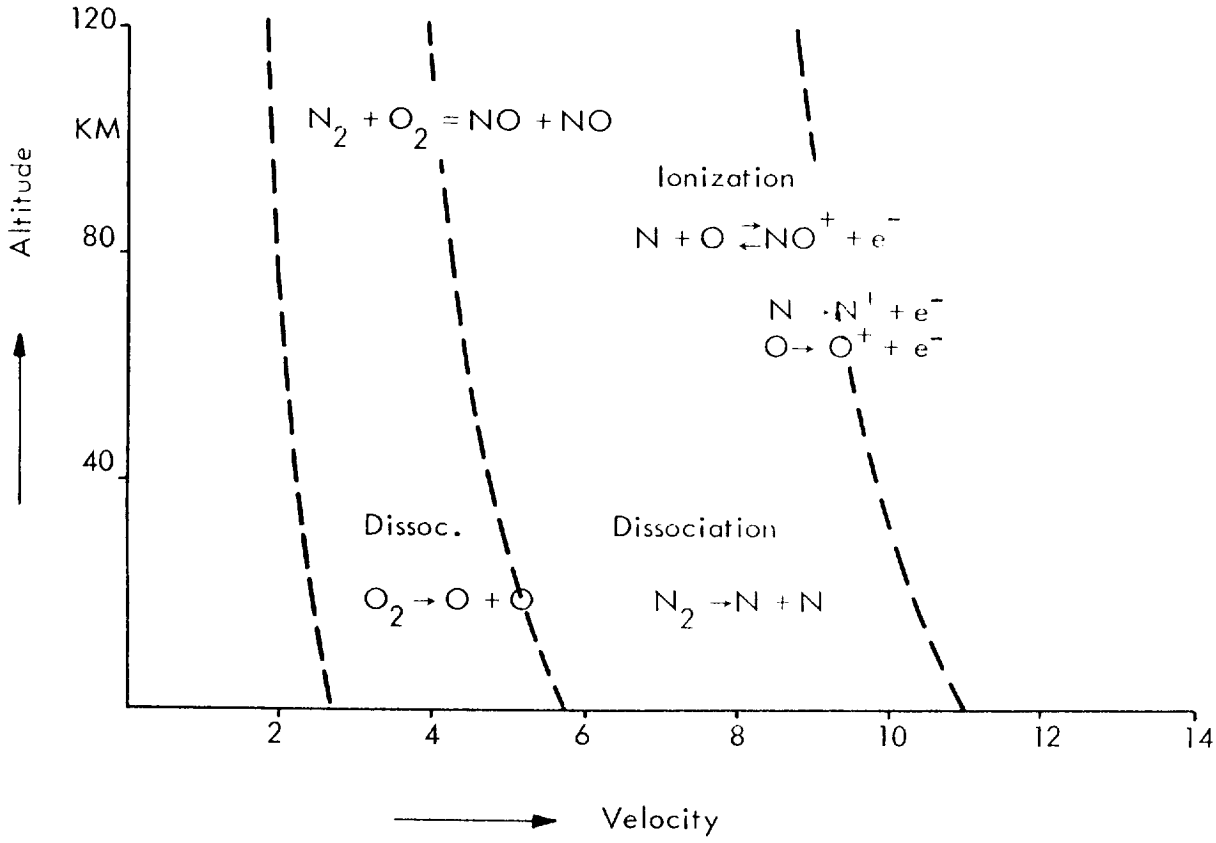

Figure 3 Inelastic collisions typical for the stagnation region of a re-entering space vehicle.

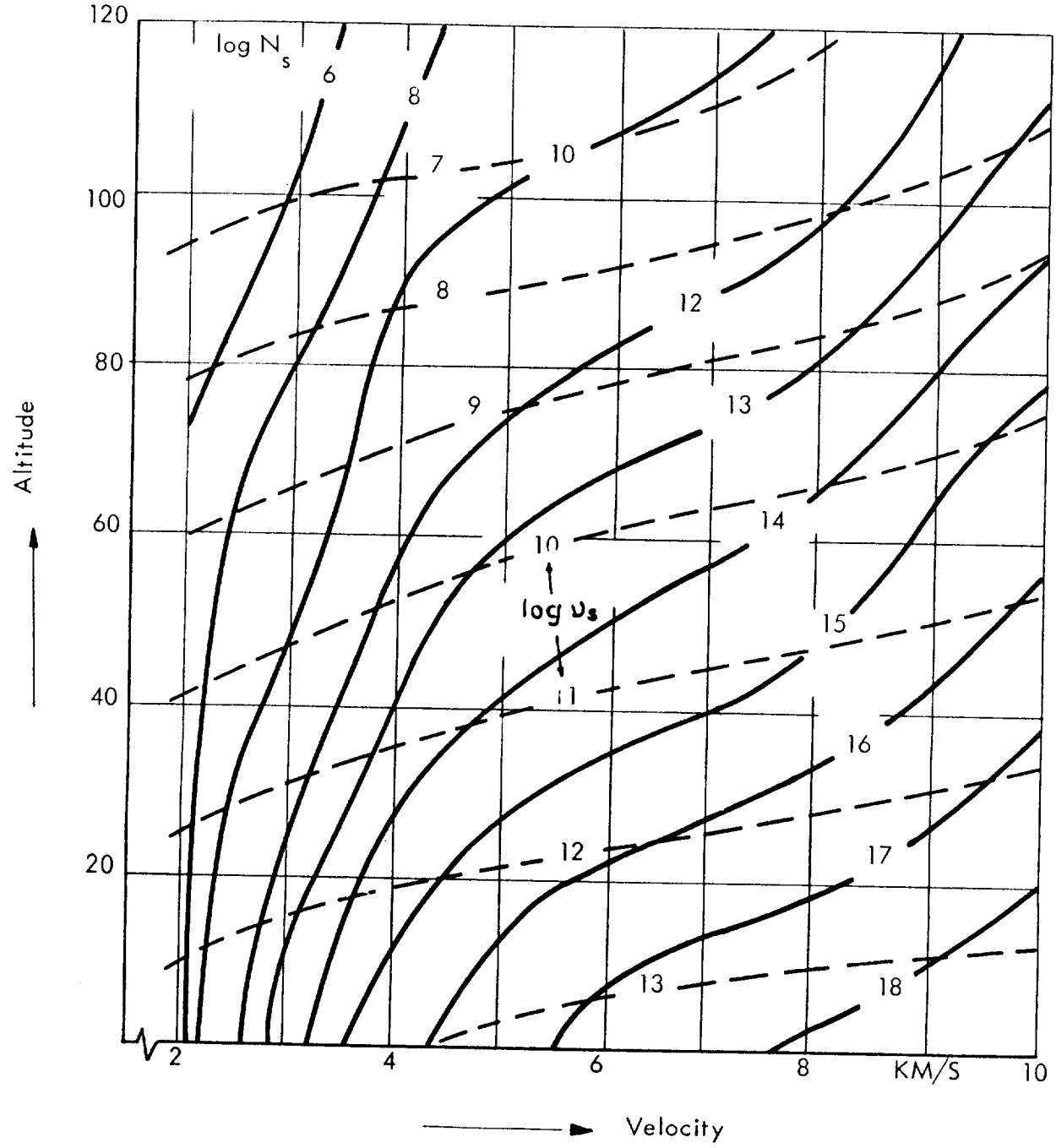

Figure 4 Electron density (log N_s) and collision frequency (log ν_s) behind a normal shock in air as a function of altitude and velocity

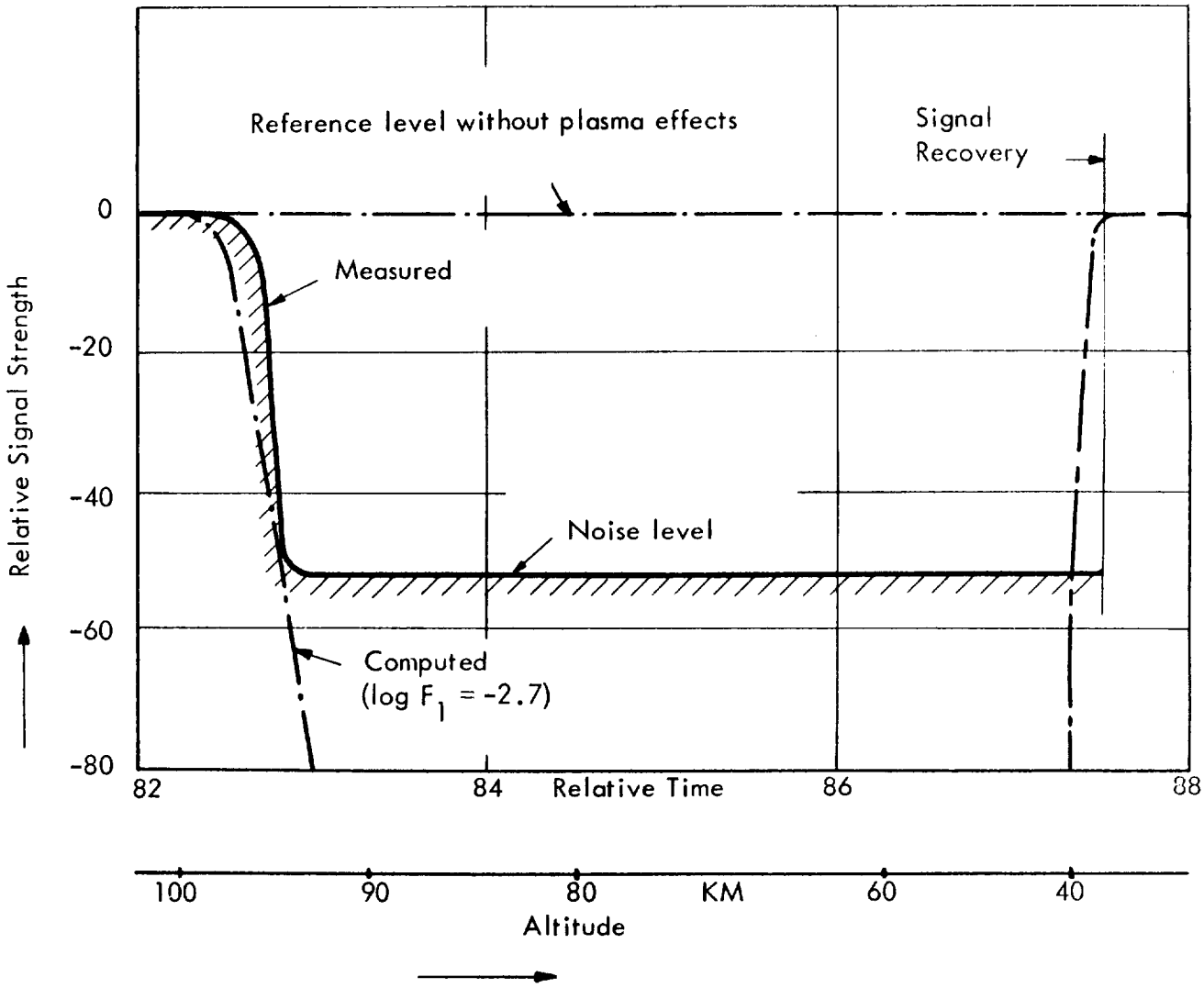

Figure 5 Relative Signal strength measured and computed for MA-6 flight during re-entry.